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Three-dimensional modeling of sediment transport in the Wuhan catchments of the Yangtze River

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Abstract

A three-dimensional flow-sediment model of the Wuhan portion of the Yangtze River was developed using the EFDC (Environmental Fluid Dynamic Code) in order to study the changing riverbed. The model was also calibrated and validated by daily measuring of the water surface elevation and using suspended sediment concentration data secured from June 1 to September 30, 2004. Based on this model, the mobile sediment on the riverbed was simulated for the high water period of the Yangtze River. The results indicate that erosion is the main issue, with maximum erosion (0.27m) occurring at the banks of Tian Xingzhou. In addition, according to a suspended sediment concentration analysis for the Han Kou Hydrologic Station section of the river, the concentration there increased from left bank to right bank.

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Keywords: EFDC; Yangtze River; flow-sediment model; erosion

1. Introduction

The Yangtze River is the longest sediment-laden river in China. It is reported that the average annual sediment discharge at the Hankou Station on the Yangtze River was about 3.84 hundred million tons between 1954 and 2005 [1]. However, the annual sediment discharge decreased significantly in recent years, after Three Gorges Reservoir was built, and this change induced the redistribution of sediment on the riverbed. Some studies show the re-suspension of contaminants while the sediment was eroded from

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the riverbed [2-4], and therefore it is now important to be sure of the movement of sediment on the riverbed.

The flow-sediment model is an efficient tool to investigate the evolution of sediment on a riverbed. The MIKE, EFDC, POM and DELFT3D software programs are the typically used flow-sediment model systems [5-10]. MIKE and DELFT3D are both business software programs, and large expenditures are required to use them. On the other hand, POM and EFDC are free software and actually more suitable for the task. POM is used mainly to simulate bays and oceans, while the EFDC can be applied to simulate rivers, estuaries, reservoirs and bays [5-8]. The EFDC (Environmental Fluid Dynamic Code) is an advanced public domain model developed by Dr. John Hamrick with funding provided by the Commonwealth of Virginia and the U.S. EPA [11]. The EFDC is designed to simulate multidimensional circulation, mass transport, and biogeochemical processes within the water column and sediment bed [5~7]. The EFDC has been continually modified and improved. Dr. Craig developed the EFDC Explorer, which includes powerful pre-processing and post-processing functions [12].

It is reported that EFDC was applied to studies of Dianchi Lake [13] and Miyun Reservoir [14] in China, but so far there has been scarce study of the Yangtze River using EFDC. Therefore, a three-dimensional flow-sediment model was constructed using EFDC, and the sediment change of the Wuhan section of the Yangtze River was simulated from June 1, 2004 to September 30, 2004. The results can be of use in reference to the operation of Three Gorges Reservoir.

2. Theory

The EFDC model's hydrodynamic component is based on three-dimensional hydrostatic equations formulated in curvilinear-orthogonal horizontal coordinates and a sigma vertical coordinate [11]. According to anelastic approximation and Boussinesq approximation, the governing equations are as follows:

The momentum equations

$$\partial_t(mHu) + \partial_x(m_y Huu) + \partial_y(m_x Hvu) + \partial_z(mwu) - (mf + v\partial_x m_y - u\partial_y m_x)Hv \quad (1)$$

$$= -m_y H \partial_x (g\zeta + p) - m_y (\partial_x h - z \partial_x H) \partial_z p + \partial_z (mH^{-1} A_v \partial_z u) + Q_u$$

$$\partial_t(mHv) + \partial_x(m_y Huv) + \partial_y(m_x Hvv) + \partial_z(mwv) + (mf + v\partial_x m_y - u\partial_y m_x)Hu \quad (2)$$

$$= -m_x H \partial_y (g\zeta + p) - m_x (\partial_y h - z \partial_y H) \partial_z p + \partial_z (mH^{-1} A_v \partial_z v) + Q_v$$

The continuity equation

$$\partial_t(m\zeta) + \partial_x(m_y Hu) + \partial_y(m_x Hv) + \partial_z(mw) = 0 \quad (3)$$

The state equation

$$\rho = \rho(p, C, T) \quad (4)$$

The transport equation for suspended sediment

$$\begin{aligned} & \partial_t(mHS) + \partial_x(m_y HuS) + \partial_y(m_x HvS) + \partial_z(mwS) - \partial_z(mw_{sj}S) \\ &= \partial_x \left(\frac{m_y}{m_x} HK_H \partial_x S \right) + \partial_y \left(\frac{m_x}{m_y} HK_H \partial_y S \right) + \partial_z \left(m \frac{K_v}{H} \partial_z S \right) + Q_s \end{aligned} \quad (5)$$

where, u , v and w are the horizontal and vertical velocity components in the curvilinear, orthogonal coordinates and sigma vertical coordinates x , y and z . m_x and m_y are the square roots of the diagonal components of the metric tensor, $m = m_x m_y$ being the Jacobian of the metric tensor determinant, A_v being the vertical turbulent viscosity, f being the Coriolis parameter, p being the physical pressure, ρ being the density, C being the salinity, T being the temperature, Q_u and Q_v being momentum source-sink terms, S being the suspended sediment concentration, K_v and K_H being vertical and horizontal turbulent diffusion coefficients, w_{sj} being a positive settling velocity, and Q_s representing external sources and sinks. In this

study, it is assumed that C equals 0 and that the density and temperature are constants. As the second-moment turbulence closure model developed by Mellor and Yamada is used [15], A_v , K_v and K_H can be determined. The system of five equations (1)–(5) provides a closed system for the variables u , v , w , ζ and S .

The numerical scheme employed in EFDC to solve the motion equations uses second-order accurate spatial finite differences. The model's time integration employs a second-order accurate three-time level finite difference scheme with an internal-external mode-splitting procedure. The EFDC model applies drying and wetting in shallow areas by a mass conservation scheme, by which the astringency of the model is improved. EFDC theory in detail can be found in Dr. Hamrick's report [11].

3. Data source and model setup

3.1. Data source

The Wuhan section of the Yangtze River was selected as the study area, as presented in Fig.1. Using 1:50000 DEM datum, a three-dimensional flow-sediment model was constructed with curvilinear-orthogonal horizontal coordinates and a sigma vertical coordinate by Seagrid and GEFDC [16]. As shown in Fig. 2, the model includes 152 by 43 grids and 4 water layers in the horizontal and vertical directions, respectively.

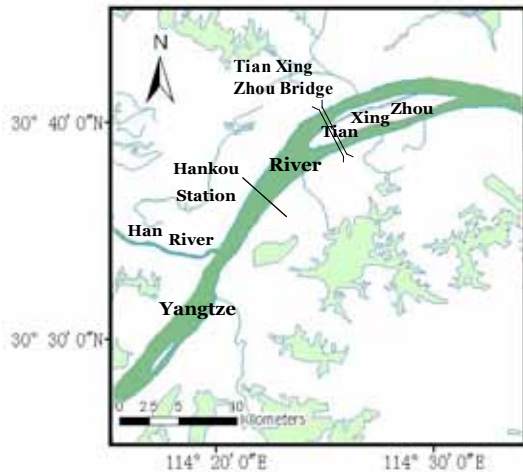


Fig. 1 Schematic diagram of study area

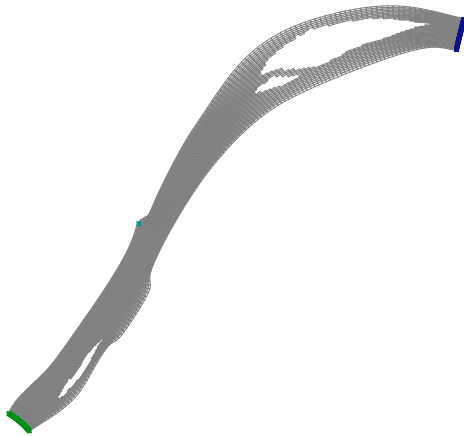


Fig. 2 Grids (Grid??) of the model

Based on the monitored hydrographic and sediment data of the Luoshan, Hankou and Xiantao stations from June to September 2004 (monitored by the Bureau of Hydrology, Changjiang Water Resources Commission), the boundary and initial condition were determined. Because of the scarcity of suspended sediment concentration (SSC) at the outflow boundary, the linear interpolation method was adopted, $S_{i,j}^n = (S_{i,j-1}^{n-1} - S_{i,j-2}^{n-1}) / 2$, where, n and $n-1$ represent No. n and $n-1$ time step, and $S_{i,j}^n$ is the SSC of i by j grid at the outflow boundary in the No. n time step. The initial water surface elevation (WSE) was set at 20.65m, the water density was 10^3 kg/m^3 , the constant temperature was 20°C . According to the dissertation of Dr. Wu [17], the initial thickness of the riverbed sediment was set at 3m and evenly divided into 3 sediment layers; in addition, 3 empty sediment layers were set. As fine sediment (less than $60 \mu\text{m}$) dominated the sorption of contaminants, the sediment on the riverbed consisted of cohesive (less than $60 \mu\text{m}$) sand in terms of grain composition test data. The initial SSC was 37.85 mg/l . The bed sediment had a density of 2 kg/l and a porosity of 0.725 [1].

3.2. Model verification

Verification of the model was done in 2 parts: verification of WSE, and verification of SSC. The predicted WSE and SSC values for Hankou Station were compared with monitored values as shown in Fig. 3.

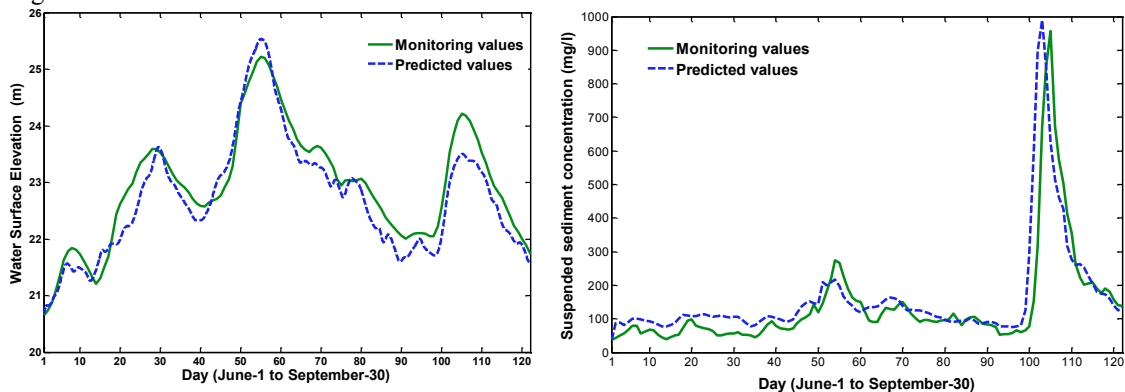


Fig. 3. (a) The comparison curves of WSE between monitored values and predicted values of Hankou Station; (b) The comparison curves of SSC between monitored values and predicted values for Hankou Station

Fig. 3(a) shows that the peak values of predicted WSE were higher than the monitored values. The main reason for this is that there are so many lakes in Wuhan, when the WSE of the Yangtze River increases, the lakes can store some floodwater. Furthermore, the model does not take into account the storage capacity of lakes locate in Wuhan, and so the predicted WSE values are higher than the monitored values. On the whole, the verifications show that the results of the modeling are satisfactory.

4. Flow and sediment simulation

4.1. WSE analysis

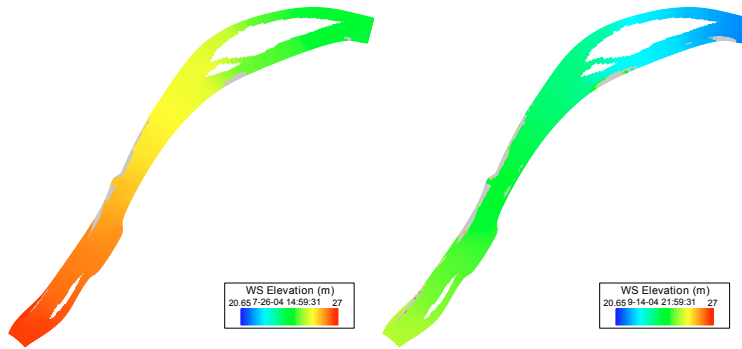


Fig.4.(a) The WSE color maps at July 1, 2004; (b) The WSE color maps at July 26, 2004; (c) The WSE color maps at September 14, 2004

The three peak values of WSE in Fig.3.(a) are for July 1, July 26 and September 14, the WSE color maps on the three days shown in Fig.4. The light blue color in the maps represents the drying point. The WSE values are seen to increase, the color changing from blue to red. Fig.4.(b) shows the WSE situation when the flood peak passed the Wuhan section of the River at 14:59 on the 26th of July 2004, and the WSE value at Hankou Station reached 25.59m (monitored value 25.22m).

4.2. Velocity analysis

The vector plots for the flow field on July 26, 2004 are presented in Fig. 5.

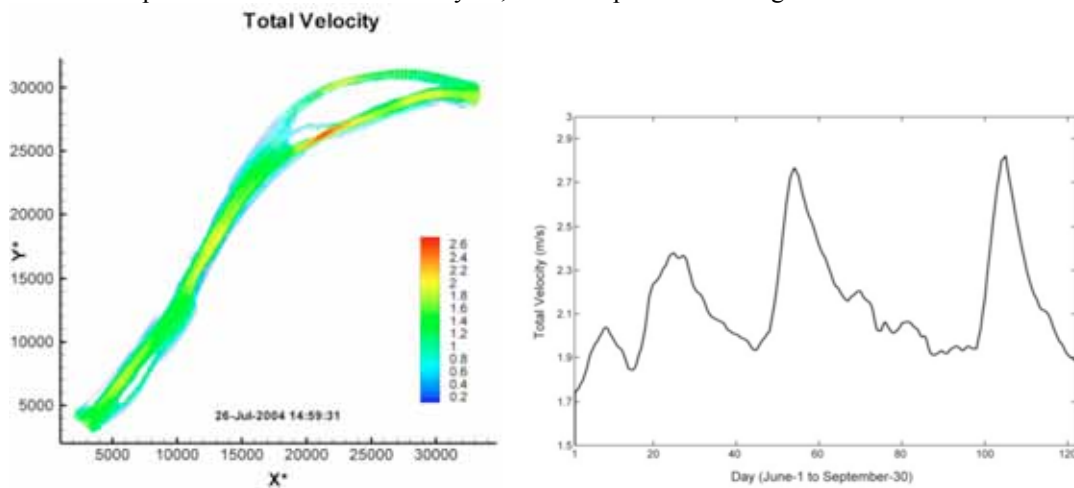
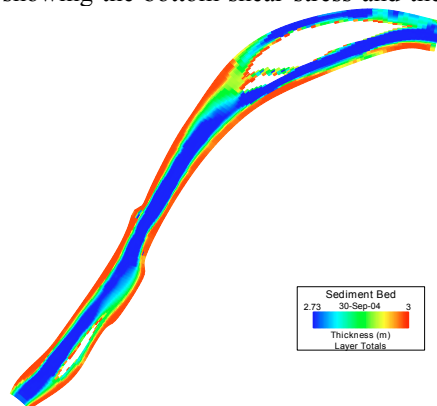


Fig.5.(a) The velocity vector diagram for the 26th of July, 2004; (b) the time-velocity diagram of the maximum total velocity point is shown in Fig.5.(a)

The maximum total velocity was seen 1.75 kilometers upstream of the Tian Xingzhou Bridge at the Tian Xingzhou right bank, the maximum total velocity being 2.63m/s. The velocity-time curve of for this extreme point is shown in Fig. 5b; the maximum velocity (2.821m/s) occurred on September 13.

4.3. Riverbed sediment analysis

The evolution of riverbed and bottom shear stress in the Wuhan section of the River were simulated by the EFDC model, Fig. 6 showing the bottom shear stress and the thickness of the riverbed sediment on



September 30, 2004.4

Fig.6.(a) Bottom shear stress diagram of the riverbed on the 30th of September, 2004; (b) the sediment thickness of the riverbed on the 30th of September, 2004

The red area in Fig.6.(a) indicates that the maximum bottom shear stress (18.69 N/m²) occurred 1.75 kilometers upstream of the Tian Xingzhou Bridge at the Tian Xingzhou right bank, and the light blue area indicates that the low bottom shear stress occurred at the left end of the Tian Xingzhou. With the action of bottom shear stress, the uniform sediment bed evolved into a new state, as shown in Fig.6.(b). The thickness of the banks was still about 3m, however the thickness in the middle of the river decreased about 0.2m. The erosion was most serious 1.75 kilometers upstream of the Tian Xingzhou Bridge at the Tian Xingzhou right bank (0.27m), as compared the erosion at the left end of the Tian Xingzhou, which was lower (about 0.1m).

As for the different thicknesses at the front of the Tian Xingzhou, the section was investigated (Fig.7).

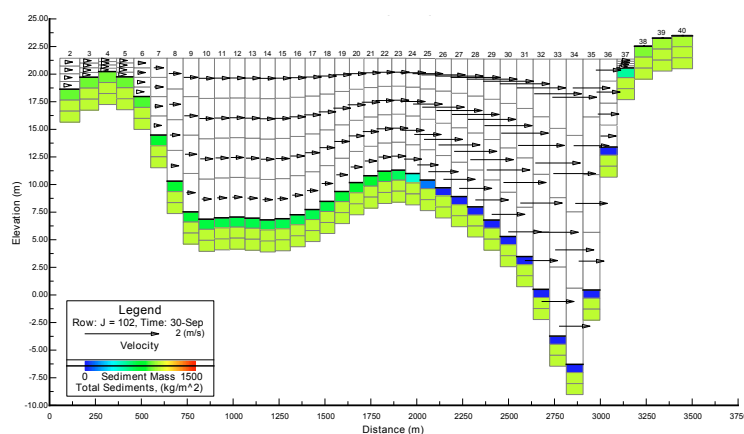


Fig.7 The sediment thickness of the section at the front of the Tian Xingzhou on September 30, 2004

As shown in Fig.7, the sediment bed in this section is shown as some color grids, while the water column is shown as colorless grids containing the velocity vector. The sediment mass can be seen to increase with a color change from blue to red. Because the initial sediment bed was uniform, Fig.7 indicates that the erosion increased from the left to right bank of the Yangtze River.

4.4. SSC analysis

The SSC peak value in Fig. 3 corresponds with the 12th of September, 2004, the SSC distribution for this day in the Wuhan section of the River and the cross-section for the Hankou Station being presented in Fig. 8.

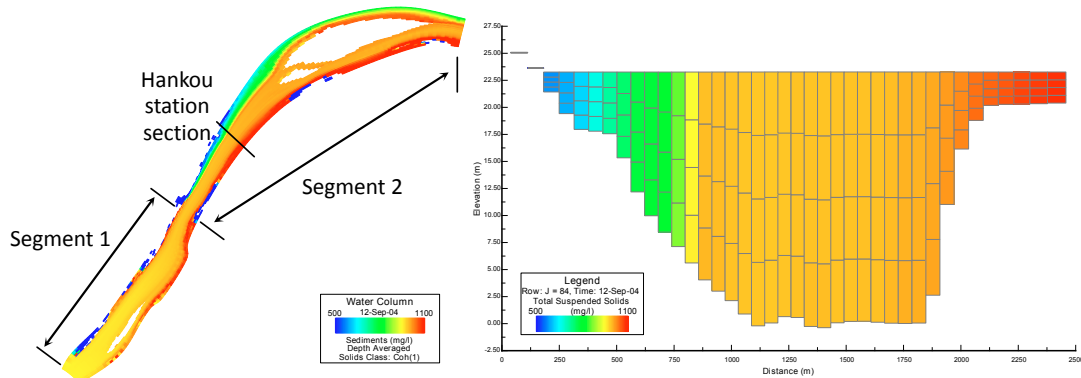


Fig.8.(a) The SSC distribution in the Wuhan section on September 12, 2004; (b) the cross-section for Hankou Station on September 12, 2004

The discontinuity of SSC distribution near the left banks is caused by wetting and drying method in calculation. The Wuhan section of the River can be divided into 2 segments in terms of the Han River estuary. In segment 1, the SSC values of the positions near the banks are higher than those for the positions in the middle of the River, nevertheless the SSC values increase from the left to the right bank in segment 2. This result indicates that the SSC of the Han River is lower than the Yangtze River on September 12, 2004. When the water comes from two rivers mixes together, the SSC nearby estuary will be lower.

5. Conclusion and discussion

The Conclusions of this study are as follows:

- (1) Using EFDC software, a three-dimension flow-sediment model for the Wuhan section of the Yangtze River is developed. The verifications show that the WSE and the SSC predicted by the model are satisfied, and the model is useful.
- (2) The WSE and flow field from June 1, 2004 to September 30, 2004 are investigated. The results show that maximum WSE (25.59m) occurred on the 26th of July, and maximum total velocity (2.63m/s) occurred 1.75 kilometers upstream of the Tian Xingzhou Bridge at the Tian Xingzhou right bank.
- (3) According to the analysis of riverbed sediment, the evolution of the Wuhan section of the Yangtze River was mainly erosion in 2004. The maximum erosion (0.27m) was found 1.75 kilometers upstream of the Tian Xingzhou Bridge at the Tian Xingzhou right bank.

(4)SSC distribution illustrates that the inflow of the Han River affect the SSC transversal distribution of the Yangtze River. As the inflow of The Han River is clearer than the water of Yangtze River on September 12, 2004, the SSC of the Yangtze Rive increase from left bank to right bank.

In this study, the uniform initial sediment bed differed from real conditions, and this should be improved on in the future. Also, the simulation of toxic contaminants in the Yangtze River is important to do, and it will be the focus of my next study.

Acknowledgements

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